10kV Integrated SiC VSD and High-Speed Motor for Gas Compression Systems

DE-EE0007253
Energy Efficiency & Renewable Energy
BP1, BP2 & BP3 8/1/2016 – 7/31/2020

Eaton Corporation
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U.S. DOE Advanced Manufacturing Office Virtual Program Review
June 2-3, 2020

Overview

Timeline

- DOE-NGEM Award issued August 2016
- Projected end date of July 2020
- Project 95% complete

Budget

	DOE Share	Cost Share	TOTAL	Cost Share %
Overall Budget	$5,444,223	$1,361,055	$6,805,278	20.00%
Approved BP 1 - 3	$5,444,223	$1,361,055	$6,805,278	20.00%
Costs as of **03/30/20**	$5,130,291	$1,282,572	$6,412,863	20.00%

Barriers

- Performance of 10kV SiC Modules
- Ancillary components
- Control of HS-PMSM Motor
- EMI: dV/dt≥100kV/µsec & di/dt≥30kA/µsec

Partners

- Cree – SiC Devices and Modules
- Calnetix – High Speed Permanent Magnet Synchronous Motor
- Carnegie Mellon University – Nano Crystalline Magnet Materials
- North Carolina State University – Control Hardware in the Loop, Saber Simulations, Dies and Gate Driver evaluations
- Novus – Systems Engineering
- PWP – System Simulation and Control Hardware in the Loop
- Petrobras – end-user, application & standards guidance

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Objective, Benefits & Challenges

Objective - Megawatt-class high-speed gas compressor systems are essential to several key industries. In their applications, size and efficiency have been essentially unchanged for decades particularly due to the use of step-up gearboxes. The end users are interested in

- reducing system footprint and volume
- lower maintenance costs
- significantly increase energy efficiency
- Improved reliability via elimination of components

Benefits to energy use and efficiency in the manufacturing sector

- This project aims to: increase efficiency by several percentage points, increase system reliability, significantly reduce maintenance costs and reduce structural requirements and cost by reducing the size of multi-megawatt-class high-speed gas compressors.
- The target energy efficiency increase is a minimum of 3%. Eaton is aiming at a 6% gain.
- Improved system reliability gain by eliminating the high speed gearbox with its lubrication system which together with the targeted motor, results in a size (foot print and volume) reduction by a factor of eight.

Challenges – The effective operation of the semiconductor modules are essential to achieve the goals outlined above. Wide bandgap high voltage semiconductor modules are novel and relatively untested. Their capabilities are much higher than those of a state-of-the-art silicon based semiconductor module which brings several challenges regarding

- Measurement
- Control
- Electromagnetic interference and dielectric compatibility

Technical Innovation

State-of-the-art and current limitations

- State-of-the-art multi-megawatt-class high speed gas compressor solutions require the use of a large low speed (1,800rpm) induction motors coupled to a gear boxes which carries a significantly sized lubrication system. The typical power level of an offshore gas compressor is 11MW delivered at 15,000rpm. The motor size is proportional to the torque it delivers at its nominal speed and the lubrication system will consume around 10% of the energy besides creating another point of failure in the system.
- Today's typical compressor system has $14m^3/MW$ inverse volumetric power density and $7.5m^2/MW$ footprint with an efficiency of 90%.

Innovative Elements

- The approach is to design and produce:
  - a 15,000rpm, 500Hz, megawatt-class, four-pole, medium voltage, permanent magnet synchronous motor
  - a MV megawatt-class, bi-directional power flow, 500Hz fundamental frequency, power dense adjustable speed drive using 10kV silicon-carbide MOSFET modules switching at 7.5kHz
- Ultra-low parasitic inverter bus bar assembly
- Specialized gate driver for voltage and current sharing with parallel 10kV SiC modules, short circuit protection and intense EMI immunity
- Dielectric coordination for ultra compact enclosure
- Inductor construction and core magnetic material
- Common-mode effect mitigation
- Current, temperature and voltage sensing under intense EMI
- Compressor system with the above innovations will have a maximum $7.4m^3/MW$ inverse volumetric power density and $3.0m^2/MW$ footprint with a minimum system efficiency of 93%. The motor size is reduced by the ratio of 15,000rpm/1,800rpm (≈8.3) due to the reduction of the required torque at 15,000rpm.

Technical Innovation Details

	Current State	DOE-NGEM
Ultra-low loop inductance bus bar	80 nH	5.0 nH
Gate driver power supply coupling capacitance:	5.0 pico-Farad typical (5pF means 0.5A noise @ 100kV/µsec with 8kV step)	1.0 pico-Farad
High voltage power semiconductor modules	6.5kV 750A Si IGBT	10kV 60A SiC MOSFET
3-phase Two-level Inverter Bridge Maximum Output Voltage	2.4kV w/ 6.5kV Si IGBT	5kV w/ 10kV SiC MOSFET
3-phase Three-level NPC Inverter Bridge Maximum Output Voltage	5kV w/ 6.5kV Si IGBT	10kV w/ 10kV SiC MOSFET
High frequency, low loss, *temperature stable inductance* filter inductors	• Metglass • Ferrite • Iron Alloy Powder • KoolMu	Nanocrystalline Cobalt-based Strain Annealed Magnetic Core
Controller noise immunity	10kV/µs	100kV/µs

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Major Elements of Innovation

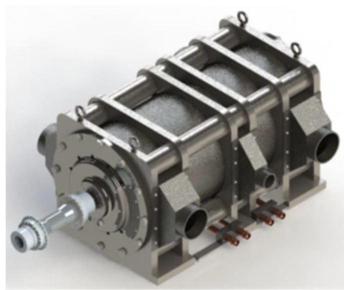
SiC MOSFET

Cree - Wolfspeed

- 10kV 10A SiC MOSFET dies, short circuit enabled
- XHV-9 (12 die/Half Bridge), 60A/Switch
- Drain-source Voltage 10kV
- Measured dV/dt ≥200kV/μsec
- Measured di/dt ≥30kA/μsec

High Speed Permanent Magnet Synchronous Motor (HS-PMSM)

Calnetix

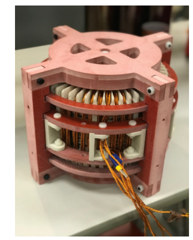


- 5kV
- 500Hz 4-pole
- 15,000 rpm
- 0.37m^3/MW
- Efficiency: 97.8%

Nano crystalline Strain Annealed Gap-less HF Core Material

Carnegie Mellon University & NASA

- 10kHz operation
- Permeability=25
- Low Losses
- Temperature & Load Parameter Stability



Ultra Low Parasitics 3-phase 1.5MW 2-Level Inverter Busbar

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Busbar Commutation Loop Parasitics

- 4.0 nanohenry for half-bridge modules
- 7.1 nanohenry for single-switch modules
- 900 picofarad stray capacitance

Control Hardware in the Loop (CHIL)

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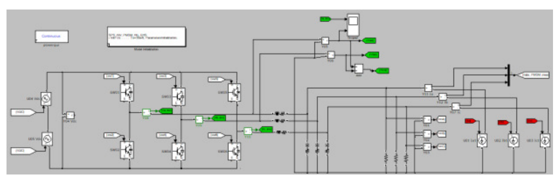

- **Physical Hardware:** Eaton's SPX Controller
- **FPGA:** Gate Driver, Input Filter, AFE, Inverter. Output Filter, HS-PMSM
  Step time 5ns, Update time 800ns

HS-PMSM Motor Control

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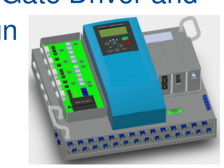
- >500Hz Fundamental Frequency
- Switching Frequency 10kHz
- Sensor less HS-PMSM Control
- EMC for ≤100kV/μs
- Application specific Gate Driver and Power Supply design



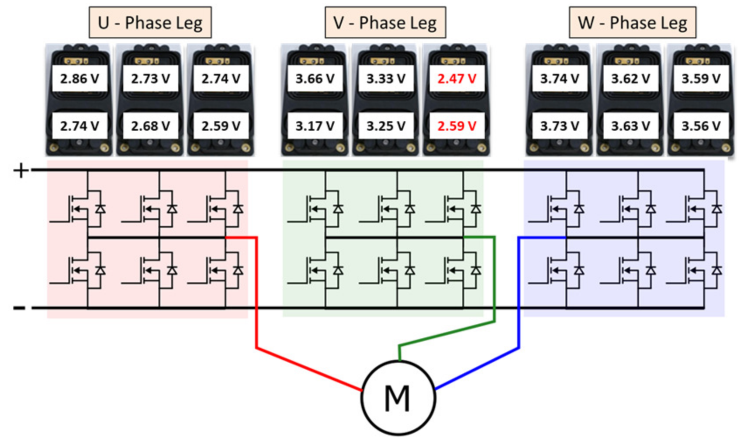
Results, Accomplishments & Status

- Control Hardware in-the-loop
  - Validated AFE and Inverter motor control using the FPGA RT model of the Calnetix 4-pole 1MW 4,235V 15,000rpm, and of the sine filter
- Gate Driver
  - Gate driver was redesigned to accommodate the differences in threshold voltage and consequent dV/dt differences of the three XHV-9 modules in parallel
  - The gate driver solution does not address the differences of the parallel die within the module
- 2-Level Inverter Bridge with three 10kV XHV-9 modules in parallel
  - Successful double pulse test at 8kVDC and RL load
  - Successful 7.5kHz continuous switching tests at 6.5kVDC Bus and 60A on a 300Hz 150HP 2400V 4480rpm induction motor
  - Performed short-circuit tests up to 7.2kVDC with redesigned gate drivers with desaturation detection
  - Common-mode filtering technique is currently in review via testing
- Adjustable Frequency Drive (AFD) Enclosure
  - Prototype was completed and all parts were fabricated
- SiC MOSFET
  - Verified the Wolfspeed XHV-9 modules thermal resistance
  - Defined the conduction and switching losses at 6kVDC to 7.2kVDC
  - Verified the partial discharge levels per IEC-1287 of the XHV-9 modules with the 1.5mm ceramic substrate. All passed 6.5kV levels but **not** 10kV
  - Determined critical characteristics for XHV-9 modules to enable proper operation in a parallel arrangement
  - Passed all of the test results and conclusions to Wolfspeed Raleigh and Fayetteville
- HS-PMSM Motor
  - Motor design completed, assembled and currently undergoing tests and final adjustments at Calnetix
  - Motor will arrive at Eaton on the 3rd week of June
- Inductors
  - CMU Cobalt Nanocrystalline Strain Annealed 440µH Inductor is currently in test with the 300Hz 4480rpm motor
  - Kool Mu 440µH Inductor is also in test
- Test stand
  - Load machine AFE VFD is currently under final control wiring process
  - Test stand will be placed in operation in the beginning of June and prior to the Calnetix PMSM arrival in the third week of June

Work to be Completed

- Finalize tests with the 300Hz motor
- Put the AFE inverter online
- Run the drive up to 500kW at 4,235V output with the water rheostat and air core inductors
- Run with the 1MW 4,235V Calnetix PMSM

Threshold Voltage Distribution of Available XHV-9



1MW 15,000rpm 4,235V 500Hz PMSM

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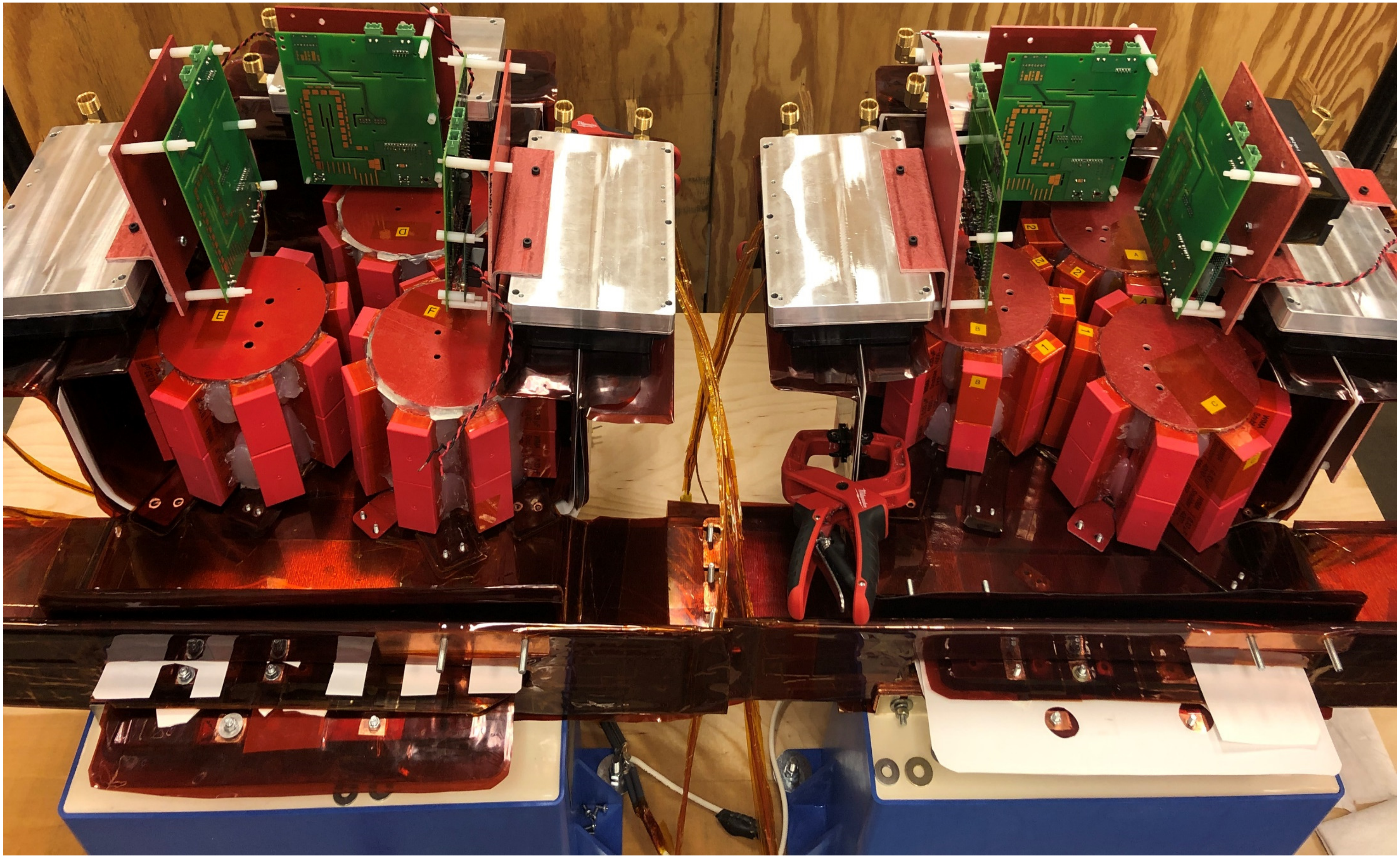
AFE and Inverter set assembled with modules and DC-link Snubbers

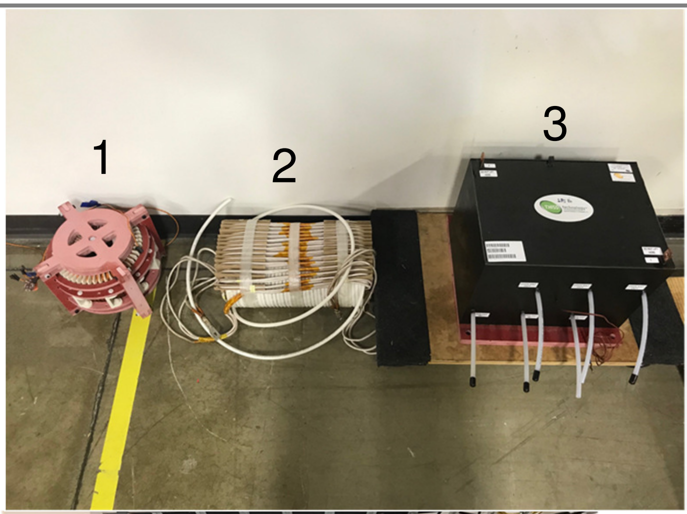


Results and Accomplishments

15,000rpm 1MW Dynamometer

Motor Weight = ~4060 lbs. (1842 Kg)
Volume = 17.7 cubic feet (0.5 m^3)

Results and Accomplishments



Filter Inductors

1. CMU/NETL
   - 12” x 12” x 8.75” – 45 lbs.
2. Kool Mu
   - 16” x 9.5” x 8.0” – 85 lbs.
3. Conventional
   - 15” x 11.75” x 10.75” – 185 lbs.

Loads Used:

1. 3,000 Gal Water Rheostat
2. Water Rheostat SS Electrodes
3. 2400V 300Hz 8-pole Induction Motor

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Results and Accomplishments

Milestones / Tasks	Status
Milestone 8.3 (M47/Q2) Delivery of 60 15kV SiC dies	In progess
Milestone 10.1 (M47/Q2) Motor Assembly and Functional Test Complete	95% Complete
Milestone 11.5 (M44 /Q1) Full protoype of the VFD assembled and fully tested	Achieved
Milestone 12.1 (M48/Q3) Project Management - Final Report content meeting DOE requirements	In progess
Milestone 13.1 (M45/Q2) System Test Plan	Achieved with new approach
Milestone 13.2 (M47/Q2) System Integration debugged and tested to 75% of target specification	Pending milestone 10.1
Milestone 13.3 (M48/Q3) Testing Complete	Pending milestone 10.1
Milestone 13.4 (M48/Q3) Data Analysis and Reporting	In progess
Milestone 14.1 (M48/Q3) Market Transformation / Commercialization Plan	In progess

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Transition (beyond DOE assistance)

Strategy for further technology development and transition to the commercial marketplace:

- The HV SiC semiconductor higher cost can be absorbed in the market place in those applications where value (reliability and system cost) permits
- The applications above require higher voltage (13.8kV) and higher power (10MW);
- The new DOE Multi-topic (topic 3.1) program aids in the utilization of the NGEM findings and developments to achieve the 13.8kV and 10MW requirements.

Commercialization partners

- O&G partners are involved by providing:
  - Application and testing guidance
  - Applicable standards for platform gas compressor equipment
  - Beta site for evaluation in a real-life scenario